

MINERAL MAPPING WITH IMAGING SPECTROSCOPY: THE RAY MINE, AZ

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1. INTRODUCTION

Mineral maps generated for the Ray Mine, Arizona were analyzed to determine if imaging spectroscopy can provide accurate information for environmental management of active and abandoned mine regions. The Ray Mine, owned by the ASARCO Corporation, covers an area of 5700 acres and is situated in Pinal County, Arizona about 70 miles north of Tucson near Hayden, Arizona. This open-pit mine has been a major source of copper since 1911, producing an estimated 4.5 million tons of copper since its inception. Until 1955 mining was accomplished by underground block caving and shrinkage stope methods. (excavation by working in stepped series

usually employed in a vertical or steeply inclined orebody) In 1955, the mine was completely converted to open pit method mining with the bulk of the production from sulfide ore using recovery by concentrating and smelting. Beginning in 1969 a significant production contribution has been from the leaching and solvent extraction-electrowinning method of silicate and oxide ores. Published reserves in the deposit as of 1992 are 1.1 billion tons at 0.6 percent copper.

The Environmental Protection Agency, in conjunction with ASARCO, and NASA/JPL obtained AVIRIS data over the mine in 1997 as part of the EPA Advanced Measurement Initiative (AMI) (Tom Mace, Principal Investigator). This AVIRIS data set is being used to compare and contrast the accuracy and environmental monitoring capabilities of remote sensing technologies: visible-near-IR imaging spectroscopy, multispectral visible and, near-IR sensors, thermal instruments, and radar platforms. The goal of this effort is to determine if these various technologies provide useful information for environmental management of active and abandoned mine sites in the arid western United States. This paper focuses on the analysis of AVIRIS data for assessing the impact of the Ray Mine on Mineral Creek. Mineral Creek flows to the Gila River. This paper discusses our preliminary AVIRIS mineral mapping and environmental findings.

2. THE RAY DEPOSIT

Early geological studies of the Ray deposit were directed to the definition of reserves, optimizing mineral recovery techniques, and aiding mining practice. An ideal ore deposit is homogeneous and isotropic, permitting a standardized mining and milling practice. In contrast, the Ray geology is complicated by faulting, host rock variation, two known episodes of tilting, a complicated enrichment history, hypogene and supergene alteration and removal of a large portion of the original ore shell. Ray Deposit mineralization is controlled by rock type, position within the deposit, faulting and enrichment history.

The Ray Deposit, Figure 1, is a sulfide system developed in a variety of Precambrian rocks and in Laramide igneous intrusives. The oldest of the Precambrian rocks is the Pinal Schist. This is a sequence of metamorphosed shale, siltstone, sandstone and conglomerate with flows or plutons of a rhyolitic (?) porphyry (Phillips *et al.*, 1974). The Precambrian Ruin Granite, a coarsely crystalline quartz monzonite, intrudes the schist but postdates the metamorphism.

Overlying the Pinal Schist and Ruin Granite are the Pioneer Formation and Dripping Spring Quartzite of the upper Precambrian Apache Group. These are quartzitic clastic rocks ranging from tuffaceous mudstone to arkosic conglomerate.

A series of Laramide intermediate to acidic dikes and stocks intrude all older rocks. These include the Tortilla Quartz Diorite, the Teapot Mountain Porphyry quartz monzonite, and the Granite Mountain Porphyry. It is thought that these porphyry intrusives were the source of the hypogene copper mineralization and contemporaneous mineral alteration of the surrounding wall rock. (Phillips, *et. al.*, 1974)

Two large faults cross the orebody, the Diabase-Ray-School Fault (the Diabase Fault) and the Emperor Fault (Phillips *et al.*, 1974). The Diabase Fault dips to the west and trends

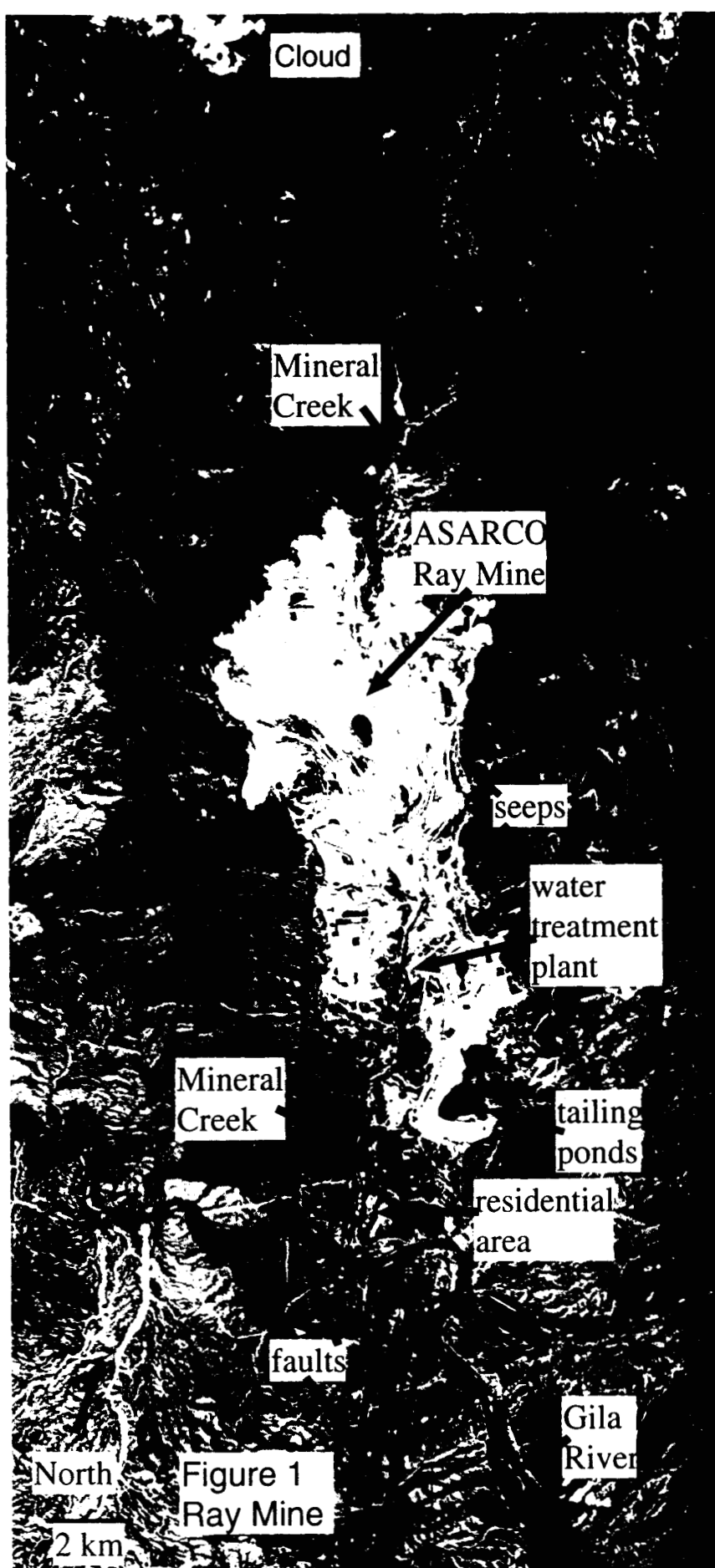


Figure 1. Ray Mine

northerly across the ore body separating the older rocks on the west from younger rocks on the east resulting in an apparent reverse movement. The Emperor Fault has shallow north or easterly dips and is considered to be a thrust. It is cut by the Diabase Fault and is known only on the west or hanging wall side of the Diabase Fault. The displacement on the Diabase Fault exceeds 1,500 feet, while the minimum movement on the Emperor Fault is about 3,000 feet with some very late movement indicated on both faults.

The zoning of Ray sulfide ore minerals is such that the central portion of the sulfide system is characterized by a low content of total sulfide and a high ratio of chalcopyrite to pyrite. The high copper zone is a "doughnut" surrounding the low-grade center and is comprised of a copper-rich chalcopyrite to pyrite mix. This is attributed to the increase in total sulfide content of this zone relative to the central portion of the deposit.

3. EPA AVIRIS PROJECT OVERVIEW

The EPA, during the analysis of risk posed to aquatic and terrestrial populations, has identified a number of contaminants in the Ray Mine Region. The primary contaminants and properties of concern to EPA are as follows: copper sulfate, copper carbonate, manganese oxide, iron oxide, arsenic, other sulfates, cadmium, temperature, pH and turbidity. Visible-near-IR imaging spectroscopy is unable to detect elemental forms of metals in a natural environment. However, previous studies in sulfide ore body settings (e.g. King *et al.*, 1995; Swayze *et al.*, 1998) show AVIRIS data can be used to map minerals that are associated with these metals, including hematite, ferrihydrite, goethite, jarosite, and alunite which are directly identifiable spectroscopically. Mineral maps can be used in the interpretation of individual mine-pile or mine operation's impacts to surface water quality and sediment composition.

AVIRIS is a useful remote-sensing tool that can be applied to accurately map diagnostic mineralogy of the Ray Mine and provide a regional geologic context for the surrounding area. This information provides both the regulator and the mining company with useful insight into the appropriate regulatory strategy. Furthermore, they provide a context in which to begin discussions on the impact of ASARCO's mining operation to the water and sediment quality in both Mineral Creek and in the Gila River. It is the synoptic understanding of the Ray Mine's contribution to regional water quality that will provide a balanced application of regulation and remediation to the environmental issues posed by mining in this region.

4. PRELIMINARY MINERAL MAPPING RESULTS

The AVIRIS data for the Ray Mine flight were converted to apparent surface reflectance using the radiative transfer methods of Green *et al.*, (1996 and references therein). The reflectance data were then mapped using the USGS Tricorder algorithm (Clark *et al.*, 1990, 1991, 1993a, 1995, 1998) testing for the presence of 253 materials. These materials included mineral, mineral mixtures, water, vegetation, environmental pollutants, and other materials. The USGS library of materials is constantly being expanded in order to fully analyze the data provided by AVIRIS. The most significant materials identified were then assembled into color-coded mineral

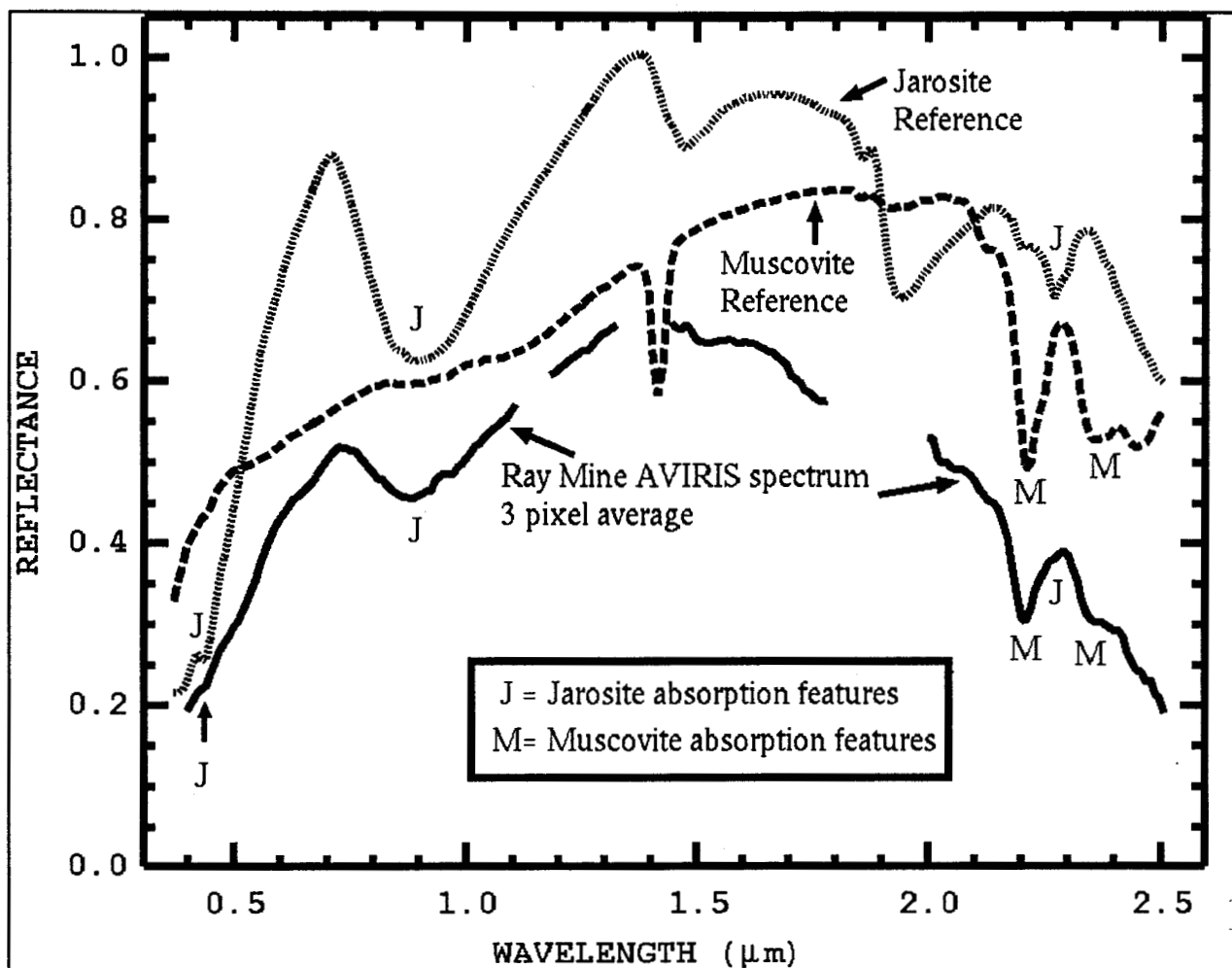


Figure 2. Spectra from the Ray Mine AVIRIS data set are compared to USGS reference spectral library (Clark et al, 1993) data. Absorption features due to jarosite are indicated by a J and those from muscovite are indicated by an M. Note how the muscovite absorptions near $2.2\mu\text{m}$ dominate the spectrum and only a very weak jarosite feature is present near $2.27\mu\text{m}$. A diagnostic jarosite feature is seen at $0.9\mu\text{m}$; the feature at $0.43\mu\text{m}$ is indicative of iron sulfate, of which there are numerous forms, one being jarosite. Tricorder correctly mapped these pixels as a combination jarosite plus muscovite. The minerals in these pixels are in an intimate mixture, explaining why the muscovite features dominate the $2\text{-}\mu\text{m}$ region.

maps. Two maps have been assembled: those having electronic absorption features in the visible and $1\text{-}\mu\text{m}$ spectral regions (below called " $1\text{-}\mu\text{m}$ maps"), and those having vibrational absorptions (typically due to OH , H_2O , and CO_3) which we call the " $2\text{-}\mu\text{m}$ map." The current map is preliminary in the sense that we have had only a short time in the field to collect samples for verification. We have also confirmed the maps by extracting spectra and identifying spectral features. In general the spectra extracted from the data set confirms the mineral maps. Minor exceptions include edges of ponds where the rocks and soils are wet. An example AVIRIS pixel of a combination of jarosite and muscovite is shown in Figure 2, compared with library reference spectra. During field verification, jarosite plus muscovite was found to be a common occurrence, confirming our mineral maps.

4A. Geologic Results

Two regions mapped as calcite, both to the north and east of the mine, consistent with known geologic formations and verified in the field. Two small areas which mapped as calcite in the preliminary mapping run showed extracted spectra that appeared to be a combination of calcite and chlorite that we did not have in our spectral database. Upon field verification these areas were indeed found to contain a mixture of calcite and chlorite. Therefore the AVIRIS data is deemed reliable for mapping these units. Most of the mapped calcite correlates well with limestone units on the published geologic maps (Cornwall, *et al.*, 1971, Creasy, *et al.*, 1983,) and the calcite-chlorite mixed pixels tended to be calcite float on chlorite rich bedrock.

The preliminary 1- μm mineral map results indicate high concentrations of iron-bearing mineralogy (Fe^{3+} -bearing minerals: hematite, goethite, jarosite, and Fe^{2+} -bearing minerals) in both the open-pit at the Ray Mine as well as in the region surrounding the mine. These initial findings are consistent with the published data on the regional and mine's geology and are considered accurate interpretations of the geologic setting. Examinations in the mine correlate well with the mapped mineralogy, however, because of mining operations, such field examinations were limited and probably always will be.

The most interesting feature within the 1- μm data is the partitioning of pyritic degradation mineralogy such that the secondary mineral jarosite was confined almost solely to the mine itself. Very few pixels of jarosite were found anywhere but within the mine. A few small outcrops of jarosite occur in the fault zones south of the Gila river. Data from similar high-acid, high-sulfide ore bodies suggests that this metal producing sequence is the single largest contributor to metal loading in streams and sediments (e.g. Swayze *et al.*, 1998, 1998). In this region, jarosite is expressed largely within the mine workings with none expressed in either Mineral Creek and only a few pixels were found in Gila River sand bars or shores. These features are most likely a result of sediment transport during the 1993 floods in the area which mobilized soils and tailings from the region into the Gila.

In the 2- μm mineral maps, we have identified clay and phyllosilicate minerals whose locations appear to portray well their locations within the areas we were permitted to examine within the mine itself. Published geologic maps (Cornwall et al, 1971, Creasy et al, 1983) and reports (Metz and Rose 1966, Phillips et al, 1974) describe lithology and hypogene and supergene alteration suites that generally contain abundant quantities of the minerals we have mapped using AVIRIS data. Our analysis finds that occurrences of three 2- μm minerals, muscovite (sericite), montmorillonite, and kaolinite stand out. Muscovite trends with occurrences of Pinal Schist. Some muscovite may be of metamorphic origin, but most is probably a result of quartz-sericite hypogene alteration. Montmorillonite is commonly found associated within high ore-grade diabase wall-rock. It may be associated with a high-grade hypogene potassic alteration (biotite-orthoclase). Metz and Rose, 1966) state that at least some of the montmorillonite and kaolinite occurring within this alteration suite is due to later supergene processes. Kaolinite in general appears to be associated with occurrences of Precambrian granite and Tertiary intrusive stocks. Its association with mineral alteration processes has not been examined in detail by this study. These findings are preliminary and correlated only with published information. Future studies may correlate our spectral analysis with detailed geologic mine maps and/or mine sampling. This is a dynamic

mine. The locations of mineral occurrences generally remain in the same place, however, transport of mine waste, processing waste and weathering products of these activities may alter the mapped locations of minerals significantly over time.

The mineral maps also display regional impacts of faulting as traced by mineral assemblages, permitting the location of both the Diabase Fault, and minor faults which surround these primary structures. Faults not indicated on published geologic maps are seen in the AVIRIS data. The maps have also portrayed the structural controls placed on both the Gila River and Mineral Creek as expressed in the morphology of both streams. Both Mineral Creek and the Gila River show evidence of structural control for their channel placement and meander features. Mineral Creek shows evidence of following an unmapped fault along its course from the exit of the mine to the Gila River. The Gila River shows meanders which appear to be controlled by a series of parallel faults trending north-south in that area.

4B. Preliminary Environmental Findings

Interpretation of the AVIRIS derived mineral maps for the Ray Mine and surrounding region show an interesting context of mining's environmental impact. While Mineral Creek does flow through the Ray Mine south to the Gila River which then flows west, there appears to be little or no jarosite contribution from the mine to the sediment or shores of either watercourse. Expanded views of both the imaging spectroscopy mineral maps along the shores and shoals of both waterways show very few pixels of jarosite outside the active mining operation. Field verification of this data indicate that there are tailings-sized materials deposited in these waterways. The single largest contributor to this lack of jarosite on in the waterways is the fact that the tailings-sized pyrite which is abundant in these sediments has had too little time to weather to its jarositic form. This lack of AVIRIS data detection indicates these deposits are below the 17-meter pixel detection of AVIRIS and that we are unable to map moderately low concentrations of unweathered sulfides. This is critical to understanding the limits to which AVIRIS is capable of indicating the release of metals to these streams. As Swayze *et al.* have demonstrated, pyrite, weathering to jarosite, forms acidic waters which can leach metals (e.g. see Swayze *et al.*, 1998) contributing to poor environmental water quality. In this region, jarosite is nearly confined to the mine pit, above the water treatment plant. Goethite, another but lessor contributor to water quality degradation (depending on low pH), is more widespread and is identified at many of the headwaters of streams draining to the Gila. Its presence in the sediments of both Mineral Creek and the Gila is expected.

The mineral maps derived from AVIRIS data show both goethite and jarosite along a series of naturally occurring seeps on the eastern edge of the pit. This would be cause for some alarm to an environmental manager. However, research indicates these seeps predate the mine and the creek is, in most places, physically separated from the mine waste source rock of acid drainage (Neil Gambell, 1998, personal communication). It is in this area that Mineral Creek courses through the mine and comes in direct contact with these high metals and low pH-bearing waters. It appears that the effect to the sediments in Mineral Creek are confined to that portion of the creek which is contained within the pit. ASARCO operates a treatment facility at the southern end of the pit to treat these waters. Based upon AVIRIS data and derived mineral maps,

ASARCO appears to be fully treating this potential waste stream prior to discharge from the mining operation, caveated by the limited (17-meter) spatial resolution of AVIRIS. Preliminary AVIRIS data analysis suggests no evidence for large scale deposition of jarositic or geothitic sediments downstream from the mine. Whether or not this regional synoptic view from AVIRIS reflects small scale environmental effects would require additional detailed field research. Reconnaissance level field research indicates metals producing outcrops throughout the region. This indicates more than one source of water quality degradation to the Gila River. It is also important to remember that the Gila River is a gaining stream. Any groundwater which follows the faulting in the area is contributing metal loading to the stream as well as the mining operations at the Ray Mine and associated processing facilities upstream in Hayden, Arizona.

This preliminary study, appropriate images, follow-on studies and related research can be found at our web site: <http://speclab.cr.usgs.gov>.

5. ACKNOWLEDGEMENTS

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